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Hæmodynamic and Cine-angiocardiographic Findings After One-stage Repair of Fallot's Tetralogy

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One-stage repair of Fallot's tetralogy is a satisfactory operative procedure with an acceptable mortality, provided the operation is undertaken by a team who are skilled in managing this heart lesion (Kirklin *et al.*, 1959; Barnard and Schrire, 1961; Malm *et al.*, 1963). The clinical results in the survivors are rewarding because the change in status is remarkable. Several recent reports on the hæmodynamics have emphasized the clinical well-being of the patients. The present study set out to confirm this clinical impression, to assess the long-term improvement in the anatomy of the outflow tract, and to study the response of the heart and pulmonary circulation to exercise.

Patients and Methods

Eleven patients with the most severe pre-operative disability who had undergone a one-stage repair operation of Fallot's tetralogy were selected from a group of 34 long-term survivors. They were cyanosed before operation with clubbing of the fingers. Three were having recurrent episodes of extreme cyanosis. They were small (below the 25th percentile of height and weight for age). The right ventricle was dominant with a short systolic ejection murmur in the pulmonary area and a loud, apparently single second sound in the aortic area. Electrocardiography, chest radiograph, cardiac catheterization, and selective angiocardiography confirmed the presence of severe cyanotic Fallot's tetralogy, with marked obstruction to the outflow tract of the right ventricle and a large right-to-left shunt through the ventricular septal defect.

Pulmonary valvotomy and infundibular resection was performed in all the patients: in 10 an outflow tract prosthesis was inserted, and in 7 it was carried across the pulmonary valve ring into the pulmonary artery. Two patients had such severe outflow tract obstruction that there was only a probe patent communication between the body of the right ventricle and the pulmonary artery. The ventricular septal defect was closed by direct suture in 6 and with a teflon patch in 5. Six patients in whom the prosthesis was extended into the pulmonary artery had severe residual pulmonary incompetence.

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The patients were all well, living a normal life, and with a near normal exercise tolerance. They were able to run up four flights of stairs, a vertical height of 60 ft. (18·3 m.), without becoming short of breath. The finger clubbing disappeared.

In the presence of pulmonary incompetence, the right ventricle was hyperdynamic with a long systolic ejection murmur heard best in the pulmonary area, a single second sound of aortic valve closure, and a diamond-shaped early diastolic murmur which was delayed 0·04 sec. after aortic valve closure. Complete right bundle-branch block was present in all the patients (Fig. 1). The pulmonary vascularity had become normal but the heart size had increased since operation. A convex left middle segment was present in patients with an outflow tract prosthesis (Fig. 2). Pulmonary insufficiency produced prominent hilar pulsation. The pre-operative polycythæmia had disappeared and the hæmoglobin concentration was normal.

The five younger children aged 7–13 years were studied at the Children's Hospital, Birmingham, in the fasting sedated state. A lytic cocktail consisting of pethidine 25 mg., promethazine 6·25 mg., and promazine 6·25 mg., in 1 ml. was given intramuscularly one hour before catheterization in a dose of 0·1 ml./kg. Venous, right atrial, and ventricular, pulmonary arterial and wedge pressures were measured through a No. 5 or 6 cardiac catheter. The intravascular pressures were recorded using an N.E.P. capacitance manometer on a Sanborn "Twinviso", hot wire stylus recorder. The mid-point of the thoracic cage was used as a zero reference level. Selective angiocardiography was performed with injection of contrast medium into the appropriate chamber using "Triosil 75%" in a dose of 0·67 ml./lb. body weight. The cine-angiocardiogram was recorded by photographing the image of a 9 in. (22·8 cm.) image intensifier on 16 mm. film using a Pailard Bolex H 16 cine camera. The finished films were viewed on a "Specto" analytical projector at a fixed film-screen distance. Pre-operative cine-angiocardiograms were available for comparison.

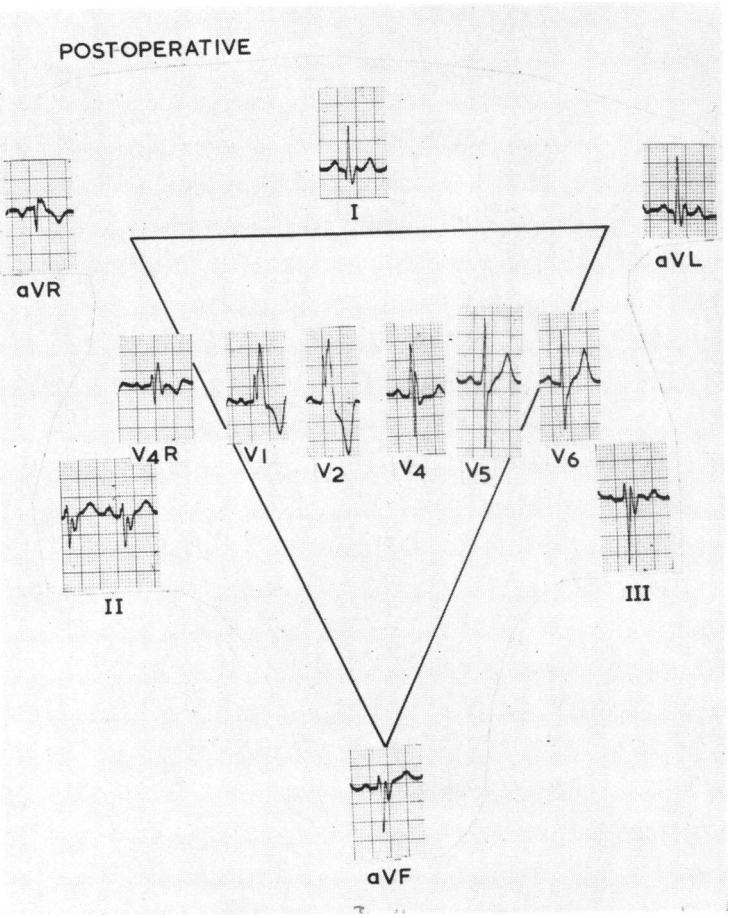

FIG. 1.—Post-operative electrocardiogram. Right bundle-branch block was seen in all the patients. It made assessment of residual right ventricular hypertrophy difficult.

The following diameters were measured: the main pulmonary artery and right pulmonary artery in diastole; the pulmonary valve ring at its lower border, and at the margin of the valve cusps; the infundibular chamber at its maximum diameter in systole and in diastole; the outflow tract in its narrowest part at the level of the crista supraventricularis in systole and diastole; the aorta in systole 1 cm. above the upper border of the sinuses of Valsalva. In each patient, the diameter was expressed as a percentage of the aortic diameter and referred to as the appropriate index, e.g.

$$\text{Ring index} = \frac{\text{Pulmonary valve ring diameter} \times 100.}{\text{Aortic diameter}}$$

The 6 adolescents and young adults aged 15–23 years were studied at the Queen Elizabeth Hospital. They did not require sedation and were studied in the fasting state to determine the effect of exercise on the hæmodynamics. Intravascular pressures were recorded through a No. 9 double lumen catheter, using capacitance manometers (Southern Instrument Co.) on a 4-channel Sanborn "Polyviso", hot wire stylus recorder. The zero reference level for pressure was 10 cm. above the plane of the catheterization table. Mean pressures were determined by planimetry, and all pressures were averaged over at least three respiratory cycles.

Arterial pressure was measured through an indwelling needle in the brachial or femoral artery.

The cardiac output was measured by the direct Fick method. Expired gas was collected in a Tissot spirometer over a period of three minutes, during which time samples of arterial and mixed venous blood were taken for the determination of the percentage oxygen saturation (Wade *et al.*, 1953). This was measured by a modification of Gatman's spectrophotometric method. The blood oxygen capacity was determined photometrically, a sample being taken during each estimate of the cardiac output. The oxygen and carbon dioxide content of gas samples were determined by the Schol-

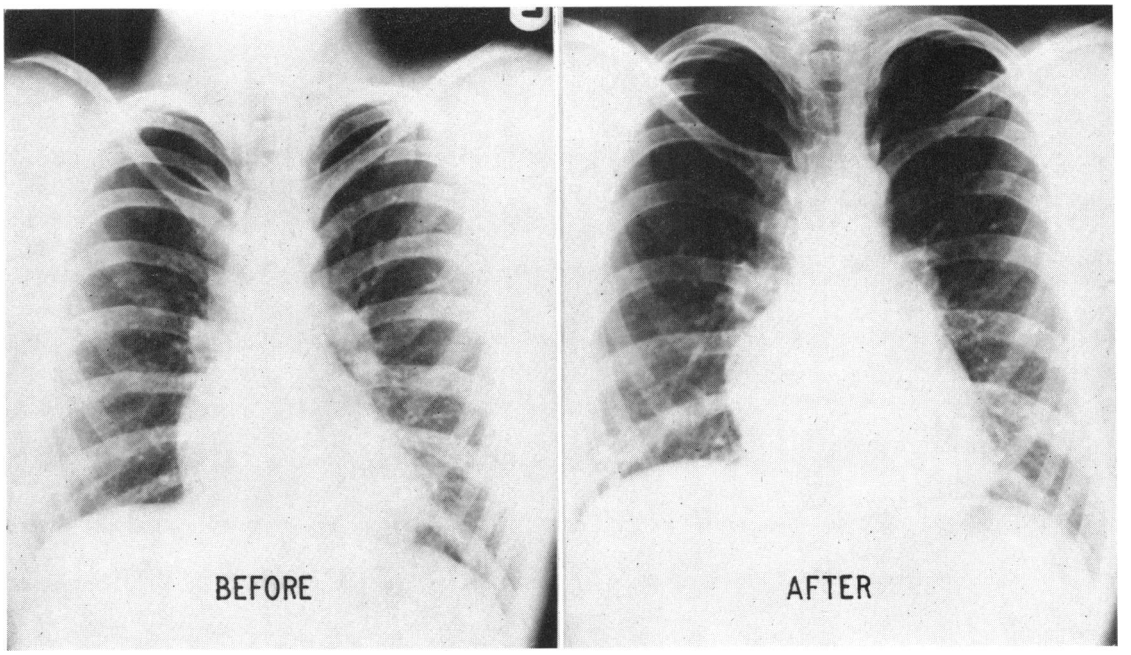

FIG. 2.—Comparison of pre- and post-operative chest radiographs (Patient K.W.). (A) Before operation: this showed the typical features of Fallot's tetralogy, pulmonary oligæmia, large left arching aorta, concave pulmonary segment, and elevated apex. (B) Three years after operaton: At the time of corrective operation, the VSD was closed by direct suture, pulmonary valvotomy was performed, and the outflow tract was enlarged with a teflon gusset. The radiograph was more penetrated than the previous film, and this masked the improvement in pulmonary vascularity. The convex bulge in the region of the left middle segment was produced by the outflow tract prosthesis. A small notch was present at the lower border of the patch.

ander micro-method, duplicate analyses being required to agree to 0·03 per cent.

Exercise was carried out in the supine position on a variable load bicycle ergometer fitted with a differential indicator which enabled a steady rate of work to be maintained. The degree of work selected for each patient was as great as could be maintained for 5 minutes without distress. This was performed with one leg only where an indwelling femoral artery needle was used. Cardiac output was measured during the fifth minute of exercise when a steady state had been reached. Simultaneous pulmonary artery and pulmonary wedge pressures were recorded immediately before the gas collection started and again immediately following its collection, the value used in the analysis being the mean of these two. Withdrawal pressure tracings were recorded when the gas collection was complete. Three samples of blood were withdrawn from each cardiac chamber and great vessel at rest, and examined for oxygen saturation to exclude any residual intracardiac shunt. Right atrial samples were also withdrawn during exercise.

TABLE IA

HÆMODYNAMIC FINDINGS

Initials and age (yr.)	Time since operation (yr.)	Nature of operation			Right atrium (mean)	Right ventricle		
		Pulmonary valvotomy	Outflow tract	Ventricular septal defect		Body		Outflow tract systole
						Systole	Diastole	
M.M. 7	2	+	Patch	Patch	5	60	5	25
B.C. 13	2	+	Patch	Suture	7	65	10	25
C.P. 7	4	+	No Patch	Suture	6	25	6	22
C.O. 10	3	+	Patch	Patch	8	30	7	16
R.T. 13	2	+	Patch	Patch	5	40	5	40

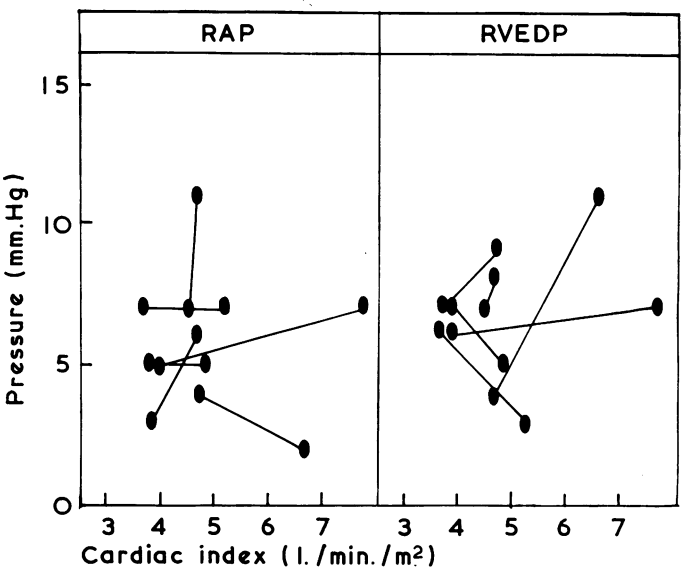

FIG. 3.—The mean right atrial pressure (RAP) and end-diastolic pressure (RVEDP) in the right ventricle at rest and on exercise. There was little change on exercise, indicating that the right ventricle could handle the increased volume load.

RESULTS

The hæmodynamic findings are given in Table I and are summarized in Tables II and III. The angiocardiographic measurements are given in Table IV.

Pressures at Rest. The right atrial pressure was raised in patients with pulmonary incompetence, with a dominant "a" wave and rapid "y" descent. Patients without pulmonary incompetence had a normal atrial pressure pulse wave form (Fig. 3).

The mean systolic pressure in the right ventricle was 40 mm. Hg, and in half the patients it was greater than the normal maximum value of 30 mm. Hg (Harvey *et al.*, 1962). The mean end-diastolic pressure in the right ventricle was also slightly raised. It was more marked in patients with pulmonary incompetence. There was a marked "dip-en-plateau" effect corresponding to the rapid "y" descent and the "a" wave in the right atrial pressure pulse.

A systolic gradient was present between the body and outflow tract of the right ventricle in 6 patients who had a raised systolic pressure in the ventricle, though this was large in only 2. Residual cristal obstruction was confirmed by angiocardiography in these 2 patients. One other patient had a gradient of 15 mm. Hg at the level of the pulmonary valve ring. Minimal narrowing of the ring was demonstrated at angiocardiography. In this patient the outflow tract prosthesis was extended as far as the ring but not across it.

Where the outflow tract prosthesis was extended into the pulmonary artery, the wave form of the

N THE FIVE YOUNGER CHILDREN AGED 7–13 YEARS

Pressures							Cardiac index	Pulmonary vascular resistance index
Pulmonary artery			Pulmonary wedge	Δ P	Brachial artery			
Systole	Diastole	Mean			Systole	Diastole	(l./min./m.²)	(units/m.²)
25	6	12	4	8	110	60	3·42	1·75
25	5	12	8	4	120	70	5·1	0·80
18	8	12	10	2	100	70	4·7	0·42
16	8	11	7	4	120	60	2·4	1·66
25	12	16	5	11	120	70	4·0	2·75

TABLE II

HÆMODYNAMIC FINDINGS AT REST AND ON EXERCISE

Initials and age (yr.)	Rest or exercise	Time since operation (yr.)	Nature of Operation			Pressures									
			Pulm. valvot.	Outflow tract	VSD	Right atrium					Right ventricle = body			Right ventricle = outflow	
						a	x	v	y	Mean	Syst.	Diast.	End-diast.	Syst.	End-diast.
A.B. 23	R	4	+	Patch	Patch	5	1	7	0	3	24	1	7	24	—
	E					7	0	7	0	6	37	1	9	35	—
M.H. 17	R	1	+	Patch	Patch	9	6	10	5	7	46	0	6	41	—
	E					7	6	9	2	7	49	0	3	46	—
P.P. 16	R	3	+	Patch	Suture	5	4	5	3	4	37	0	4	34	—
	E					3	1	5	0	2	51	0	11	41	—
K.W. 18	R	3	+	Patch	Suture	8	5	7	4	7	31	1	7	28	—
	E					10	5	9	4	11	40	1	8	38	—
B.W. 15	R	2	+	Patch	Suture	10	3	8	2	5	31	2	7	31	—
	E					7	2	6	1	5	35	2	5	35	—
B.J. 19	R	4	+	Patch	Suture	9	3	7	3	5	43	2	6	27	—
	E					10	3	7	4	7	45	7	7	35	—

pressure pulse in the proximal part of the artery containing the patch resembled the right ventricular tracing, indicating that the right ventricle and proximal pulmonary artery formed part of a continuous chamber. Beyond the upper border of the patch, the wave form altered. The systolic pressure was lower by 3–10 mm. Hg and the diastolic pressure increased by 3–4 mm. The average systolic, diastolic, and mean pressures in the pulmonary artery were normal, and only one patient exceeded the normal mean pressure of 18 mm. Hg (Segel *et al.*, 1964). The individual systolic and diastolic

TABLE II

MEAN VALUE OF HÆMODYNAMIC MEASUREMENTS AT REST

	Mean	Normal value (Segel *et al.*, 1964)
All patients		
Pressures (mm. Hg)		
Right atrium—mean	5	
Right ventricle—body		
Systole	40	
End-diastole	6	
Right ventricle—outflow		
Systole	28	
Pulmonary artery		
Systole	28	24·9 ± 4·9
Diastole	7	11·4 ± 3·1
Mean	14	17·9 ± 3·2
Pulmonary wedge	8	10·5 ± 2·7
Δ P	6	
Systemic artery		
Systole	128	136·0 ± 17·7
Diastole	78	79·8 ± 10·1
Cardiac index (l./min./m.^{2})	4·00	4·04 ± 0·64
6 patients aged 15–23 only		
Heart rate/min.	83	89·9 ± 12·2
Stroke volume (ml./m.^{2})	50	45·8 ± 9·1
Resting ventilation (l./min./m.^{2})	3·75	4·94 ± 1·84
% oxygen extraction	4·25	
O_2 uptake (ml./min./m.^{2})	158	143 ± 16·7
Arteriovenous oxygen difference (vol. %)	3·94	3·60 ± 0·62

TABLE III

MEAN VALUE OF HÆMODYNAMIC MEASUREMENTS ON EXERCISE (PATIENTS AGED 15–23 YEARS ONLY)

	Mean	Normal value (Donald *et al.*, 1955)
Pressures (mm. Hg)		
Right atrium	6	
Right ventricle—body		
Systole	43	
End-diastole	7	
Right ventricle—outflow tract		
Systole	39	
Pulmonary artery		
Systole	35	
Diastole	10	
Mean	19	
Pulmonary wedge	10	
Δ P	9	
Systemic artery		
Systole	144	
Diastole	101	
Ventilation (l./min./m.^{2})	10·1	7·28
% oxygen extraction	4·76	6·30
Oxygen uptake (ml./min./m.^{2})	449	460
Arteriovenous oxygen difference (vol. %)	8·21	6·62
Cardiac index (l./min./m.^{2})	5·60	6·60
Heart rate/min.	118	—
Stroke volume (ml./beat)	47	—

ADOLESCENTS AND ADULTS AGED 15–23 YEARS

Pulmonary artery			Pulm. wedge	⊿ P	Brachial artery		Ventil. (l./min.)	% O_2 extraction	O_2 uptake (ml.)	A-V O_2 diff. (vol. %)	Cardiac output (l./min.)	Cardiac index (l./min./m.²)	Pulm. vasc. resist. (units)	Heart rate/min.	Stroke vol. (ml.)
Syst.	Diast.	Mean			Syst.	Diast.									
24	9	14	11	3	140	80	8·92	4·23	377 (189)	4·92	7·66	3·83	0·39 (0·78)	60	127 (67)
34	17	25	13	12	170	110	14·05	6·17	867 (434)	9·32	9·30	4·65	1·29 (2·58)	92	101 (50)
36	11	19	11	8	150	90	5·55	4·24	235 (159)	4·38	5·37	3·63	1·48 (2·20)	75	72 (48)
44	11	22	11	11	145	118	26·72	3·29	879 (594)	11·58	7·59	5·13	1·45 (2·15)	120	64 (43)
33	6	15	6	9	144	96	5·39	5·16	278 (167)	3·61	7·70	4·64	1·16 (1·94)	110	70 (42)
26	11	16	9	7	170	115	21·57	4·04	871 (525)	7·94	10·97	6·61	0·64 (1·05)	145	75 (45)
26	4	11	7	4	130	88	4·97	3·98	197 (134)	3·02	6·56	4·50	0·61 (0·89)	90	73 (50)
38	6	17	10	7	142	92	7·83	6·17	483 (322)	7·23	6·68	4·60	1·04 (1·52)	104	64 (44)
30	6	14	8	6	138	90	6·22	3·87	241 (163)	4·20	5·74	3·88	1·04 (1·54)	86	67 (45)
35	5	15	9	6	146	90	11·02	4·68	516 (349)	7·17	7·20	4·87	0·83 (1·23)	108	67 (45)
27	9	15	10	5	128	80	5·34	4·05	216 (138)	3·53	6·12	3·92	0·82 (1·27)	75	82 (52)
35	10	18	11	7	122	82	17·19	4·26	732 (469)	6·05	12·10	7·76	0·58 (0 92)	140	86 (56)

pressures in the pulmonary artery were difficult to interpret, in view of the associated pulmonary insufficiency. Patients with severe pulmonary insufficiency, as judged by the length of the early diastolic murmur in the pulmonary area, had a wide pulse pressure with a high systolic and low diastolic pressure.

The mean pulmonary wedge pressure, pressure difference across the pulmonary vascular bed (⊿P), and pulmonary vascular resistance were also normal, (Fig. 4).

Cardiac Output at Rest. Oxygen uptake was measured at rest in 6 patients, 5 of whom had pulmonary insufficiency. In these patients the mean resting cardiac index, arteriovenous oxygen difference, and resting stroke output were normal, according to the criteria of Wade and Bishop (1962) and Segel *et al.* (1964). The mean values for the group are compared with the normal values in Table II. The mean resting ventilation, oxygen extraction, and oxygen uptake were also normal.

Effect of Exercise (Fig. 3–5). The results in the present group of 6 patients were compared with 4 normal subjects studied under similar conditions with a comparable work load (Group II of Donald *et al.*, 1955). The mean results are compared in Table IV. The cardiac output was slightly lower and the arteriovenous oxygen difference slightly higher than in the control group, but the mean value for the arteriovenous oxygen difference fell within the 95 per cent confidence limits of the rectangular hyperbola relating arteriovenous oxygen difference

TABLE IV

ANGIOCARDIOGRAPHIC MEASUREMENTS BEFORE AND AFTER A CORRECTIVE OPERATION FOR FALLOT'S TETRALOGY

Initials	Before operation							After operation						
	Cristal index		Infundibular index		Ring index	Main pulmonary artery index	Right pulmonary artery index	Cristal index		Infundibular index		Ring index	Main pulmonary artery index	Right pulmonary artery index
	Systole	Diastole	Systole	Diastole				Systole	Diastole	Systole	Diastole			
B.C.	17	24	41	55	52	72	52	56	60	44	120	—	80	80
C.P.	20	67	—	—	60	66	53	133	167	100	133	100	100	75
M.M.	40	60	40	60	60	60	80	125	144	94	125	63	94	86
C.O.	8	17	—	58	50	42	50	37	83	83	87	67	100	57
R.T.	16	22	44	46	38	47	—	94	125	121	156	78	94	62
Mean	20	38	42	55	52	57	59	89	124	89	124	77	94	72

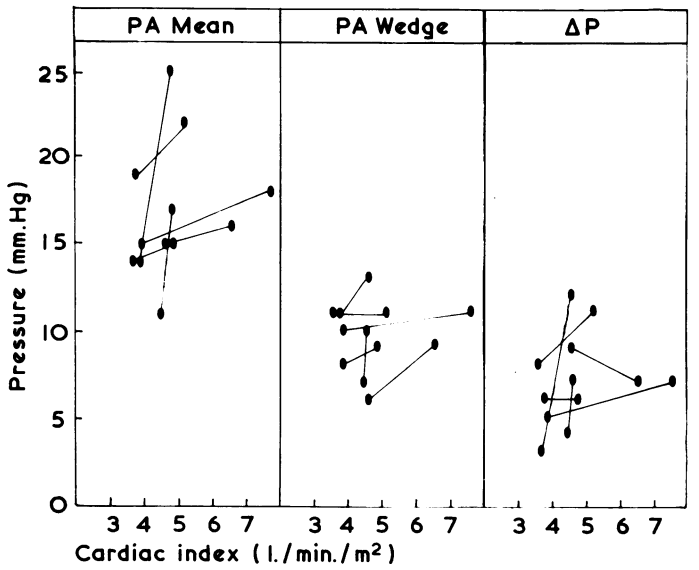

FIG. 4.—The mean pulmonary artery and pulmonary wedge pressures and pressure gradient across the pulmonary vascular bed (ΔP) at rest and on exercise after the one-stage repair operation. In each patient the pressure is related to the cardiac index as the given level of exercise. The response to exercise was normal, though Δ P increased conspicuously in one patient, the oldest in the group.

to oxygen uptake (Wade and Bishop, 1962). Moreover, when a patient with a thrombosed left main pulmonary artery was excluded, the patients all fell within these confidence limits. There was no increase in stroke index during exercise—a normal response (Wade and Bishop, 1962).

The mean pressure in the pulmonary artery increased 1 mm. above normal, but the pulmonary wedge pressure and pressure gradient across the pulmonary vascular bed were normal. In one patient, the oldest in the group, Δ P increased conspicuously (Table III).

The end-diastolic pressure in the right ventricle increased slightly to 10 mm. Hg and was associated with a similar increase in right atrial pressure with a prominent "a" wave.

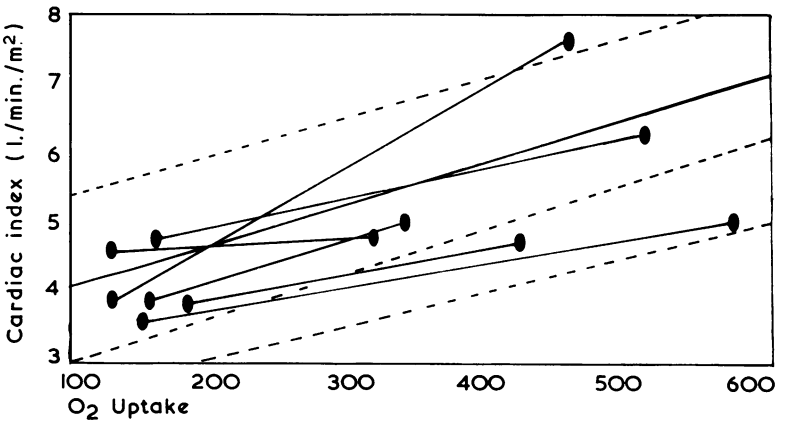

FIG. 5.—The response of the cardiac output to exercise. The solid diagonal line represents the mean normal values. The dotted lines on each side represent the 95% confidence limits for normal subjects, and the lower dotted line, the lower limit for patients with mitral stenosis and Grade I impairment (Donald *et al.*, 1955). The response to exercise was normal in 5 of the 7 patients and slightly impaired in 2. The mean response of the group was normal. (Oxygen uptake is given in ml./min./m.²)

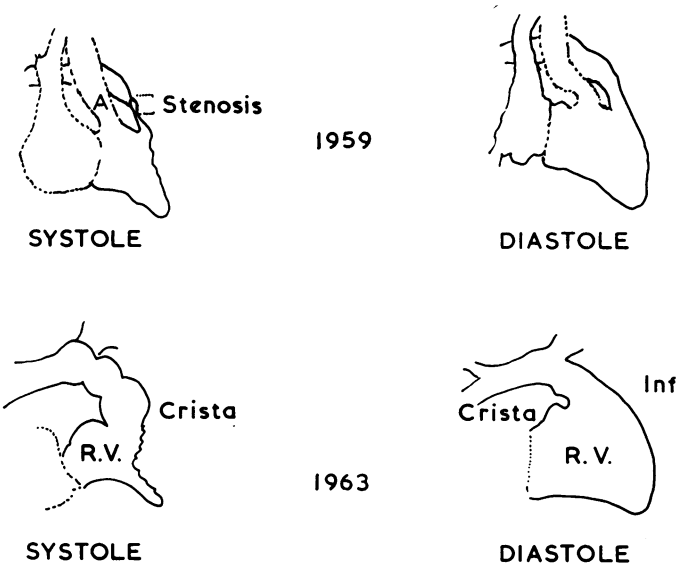

FIG. 6.—Tracings from pre- and post-operative cine-angiocardiograms (right anterior oblique position). 1959: before operation, there was severe outflow tract obstruction (valvular and infundibular), and a large right-to-left shunt. 1963: one year after operation. The outflow tract obstruction was relieved by pulmonary valvotomy, resection of infundibular muscle, and insertion of an outflow tract gusset extending from the body of the right ventricle, across the pulmonary valve ring, and enlarging the proximal half of the main pulmonary artery. There was no residual obstruction, but moderate pulmonary insufficiency was present.

The mean ventilation was 10·2 l./min./m^2. compared with 7·28 l./min./m.^{2} for the control group, indicating that oxygen extraction was less and ventilation more inefficient than normal in this group of patients.

Selective Angiocardiography. Selective right ventricular angiocardiography was performed in 5 patients (Fig. 6 and 7). The right ventricle was dilated. The region of the outflow tract patch (4 patients) was inert, but less transmitted pulsation was present than in comparable patients who were left with a residual ventricular septal defect after surgery. The end-diastolic and end-systolic volumes of the right ventricle were increased in patients with pulmonary insufficiency. This was assessed by eye only since cine-angiocardiograms were recorded to produce optimal results, and simultaneous photography in two planes was not performed. Moreover magnification factors varied in individual patients. Residual obstruction was due to a prominent crista supraventricularis in 2 patients. There was no reflux of contrast medium into the right atrium. Considerable pulmonary artery pulsation was present.

Angiocardiographic indices increased after operation (Table IV). The main and right pulmonary artery indices increased as well as the indices of those regions treated by surgery. The former improvement was, therefore, a passive response to an increase in pulmonary artery pulsation and blood flow.

Small slow injections of contrast medium were made into the pulmonary artery in 2 patients placed in a postero-anterior position. Forward blood flow during systole was rapid and the contrast was washed away. The pulmonary valves were not shown. Pulmonary incompetence was demonstrated in one patient. There was *great* pulsation of the pulmonary vessels. The actual forward stroke volume was much larger than normal, as estimated by the rate of disappearance of the contrast medium. This indicated considerable regurgitant flow since the effective net stroke volume was normal.

DISCUSSION

Complete repair of Fallot's tetralogy is a difficult operative procedure (Smith *et al.*, 1965). In patients with mild outflow tract obstruction and a bidirectional shunt or left-to-right shunt through the ventricular septal defect, the pulmonary valve is often normal and there are few structural changes in the small pulmonary arteries. The operative mortality is low. With more severe outflow tract obstruction, a small pulmonary valve ring, reduced pulmonary blood flow, and multiple thromboses in the small pulmonary arterioles, complete repair is

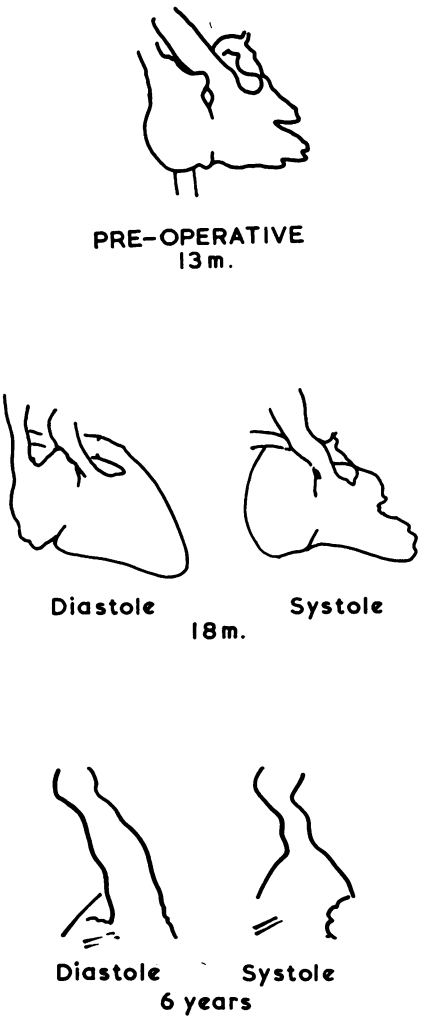

FIG. 7.—Tracings from pre- and post-operative cine-angiocardiograms (right anterior oblique position). 13 months: venous cine-angiocardiogram. There was severe outflow tract obstruction—infundibular obstruction with a prominent crista supraventricularis, valvar pulmonary stenosis with a narrow valve ring. Early aortic opacification during the dextrogram phase confirmed the presence of a large right-to-left shunt through the ventricular septal defect. 18 months: selective right atrial cine-angiocardiography 2 years before corrective surgery was undertaken. 6 years: selective right ventricular cine-angiocardiography performed 2½ years after corrective surgery. Pulmonary valvotomy and infundibular resection were performed and a small gusset was inserted into the outflow tract of the right ventricle at operaton. The tracings demonstrate improvement though slight residual obstruction is still present.

more formidable, a large outflow tract prosthesis is required, and the mortality of operation is increased. If the prosthesis is inserted into the outflow tract only, there is little pulmonary insufficiency after valvotomy. However, death occurs in the immediate post-operative period if the pressure gradient between the right ventricle and pulmonary artery is not relieved at all (Kirklin *et al.*, 1959). A large prosthesis extending across the pulmonary valve ring to the bifurcation of the pulmonary artery is, therefore, required in these patients if they are to survive operation. This often produces free pulmonary incompetence increasing the stroke volume and work of the right ventricle. The patients who were studied were selected because of their preoperative disability, the extensive nature of the repair, and the residual post-operative pulmonary insufficiency.

Pressures. Normal or near-normal post-operative hæmodynamic findings have been reported by several authors (Kirklin *et al.*, 1960; Kay *et al.*, 1959, 1961; El Sayed, Bentall, and Melrose, 1962; Bahnson *et al.*, 1962; Bristow *et al.*, 1962; Allison *et al.*, 1963; Theye and Kirklin, 1963; Malm *et al.*, 1963; Albertal, Swan, and Kirklin, 1964). In our patients there was no pulmonary arterial hypertension at rest or on exercise (apart from one patient with a thrombosed left main pulmonary artery) and the pressure gradient across the pulmonary vascular bed was normal. Rich (1948), Brown *et al.*, (1956), Dammann and Ferencz (1956), Ross, Taussig, and Evans (1958), and Ferencz (1960a, b) described multiple thrombotic lesions in the small pulmonary arteries and veins in patients with pulmonary stenosis, polycythæmia, and reduced pulmonary blood flow. The older patients in the present group were deeply cyanosed and polycythæmic at the time of operation, and multiple thromboses were present in the small pulmonary arteries of comparable patients who died at operation. Recanalization of these thrombosed vessels must, therefore, have occurred when the pulmonary blood flow and pulse pressure were restored to normal. This was observed in 2 other patients who died 9 weeks after the corrective operation. We did not observe pulmonary hypertension which occurred if an anastomotic operation produced a large communication between the systemic and pulmonary arteries (Ross *et al.*, 1958). Even on exercise our patients had a normal or only slightly raised gradient across the pulmonary vascular bed, indicating that the bed had sufficient capacity to accommodate the increase in pulmonary blood flow.

When pulmonary incompetence was present there was marked hilar pulsation, the catheter tip moved vigorously back and forth in the pulmonary artery, and the pulmonary artery pulse pressure widened. The raised end-diastolic pressure in the right ventricle produced a "dip-en-plateau" appearance of the diastolic pulse contour. A corresponding increase in right atrial pressure was present with dominant "a" and "v" waves and a rapid "y" descent. The high end-diastolic and right atrial pressures were absent in patients with little residual pulmonary insufficiency. There were three possible explanations for the raised end-diastolic pressure and altered right atrial pressure pulse contours: pulmonary insufficiency with equalization of pulmonary arterial and right ventricular pressures during diastole, failure of the right ventricle, or diminished compliance of the ventricular wall, and an inability to relax during diastole. In patients with Fallot's tetralogy who were studied before operation, the end-diastolic pressure was raised (4–8 mm.), indicating diminished compliance of the ventricle or an augmented filling pressure which was required for right ventricular ejection against the severe pressure load imposed by the outflow tract obstruction.

These findings and comparable personal observations in patients during the immediate post-operative period after cardiopulmonary bypass provided a clear picture of the complex hæmodynamic changes following one-stage repair. Immediately after operation patients with a simple atrial septal defect required a mean central venous pressure of 5–8 mm. Hg to maintain an adequate cardiac output and systemic blood pressure. This increased to 7–10 mm. Hg in patients with a ventricular septal defect needing ventriculotomy; 10–12 mm. Hg in patients with mild Fallot's tetralogy in whom infundibular resection and/or pulmonary valvotomy was necessary; and 12–20 mm. Hg in those with severe tetralogy of Fallot who had residual pulmonary insufficiency. In the last group, the right atrial pressure was significantly higher than the left atrial pressure measured at the end of operation. This high central venous pressure persisted for 6–12 hours after operation, and only returned to normal 3–4 days later. Three patients included in the present study had a very high central venous pressure after operation and developed transient, but severe, cardiac failure lasting 1–2 weeks (Theye and Kirklin, 1963). Under these conditions right ventricular function was compromised by cardiopulmonary bypass with prolonged ventricular fibrillation and myocardial hypoxia, a large ventriculotomy dividing small branches of the coronary arteries, alteration in the mode of contraction of the right ventricle after resection and division of the muscular trabeculæ, tricuspid incompetence produced by traction on the valve ring after closure of the ventricular septal defect and overdistension of the right ventricle, and pulmonary incompetence. The findings in the venous pulse after operation confirmed that each factor contributed towards reduced right ventricular function in the immediate post-operative period, but this returned to normal 24 hours to one week later.

At the time of post-operative investigation, the end-diastolic pressure in the right ventricle and the right atrial pressure were normal in patients with little or no pulmonary incompetence, but were raised in the presence of severe incompetence. Pulmonary incompetence was, therefore, the main factor responsible for the raised pressure. The raised pressures increased only slightly on exercise, so that these patients with pulmonary incompetence were able to undertake exercise without a marked increase in right atrial pressure and right ventricular

failure. It should be emphasized that the normal response of the cardiac output to exercise indicated that left ventricular function and filling were normal while the constancy of the right atrial pressure (in 5 of the 6 patients) indicated that the right ventricle was able to function in a normal manner under the conditions of the study.

Only two patients had moderate or severe residual obstruction to the outflow tract of the right ventricle. In two others it was mild when observed at angiocardiography, so that the residual pressure gradient must have been due in part to the augmented stroke volume, a hæmodynamic picture resembling atrial septal defect with a large pulmonary blood flow. The presence of these residual pressure gradients indicated that careful reconstruction of the outflow tract—crista supraventricularis, infundibular chamber, and valve ring—was required at operation: to relieve as much obstruction as possible without producing severe incompetence.

Blood Flow and Cardiac Output. The cardiac output and arteriovenous oxygen difference at rest were normal. The response of the cardiac output to exercise was normal, though the arteriovenous oxygen difference increased more than in comparable control subjects. The stroke volume response to exercise was also normal, indicating normal left ventricular function and proving that the right ventricle was able to handle the increased volume load. Johnson (1962) found that the response of the cardiac output to exercise was subnormal after pulmonary valvotomy in patients with pulmonary stenosis. His patients were older and had a higher pre-operative pressure in the right ventricle so that myocardial fibrosis may have been present. Two patients in the present group had a patent foramen ovale. Arterial oxygen desaturation on exercise was not observed, though right atrial pressures were raised indicating that a residual patent foramen ovale could not be the cause of the impaired response of the cardiac output to exercise.

Oxygen Consumption and Ventilation. A comparison with the data of Davison, Armitage, and Arnott (1953) showed that oxygen uptake was unaltered in children with cyanotic congenital heart disease. The abnormal increase in ventilation and reduction in oxygen extraction on exercise indicated inefficient ventilation. The underlying mechanisms were not studied, but the findings suggest that pulmonary incompetence or residual changes in the pulmonary vessels were responsible for these abnormalities.

Angiocardiographic Improvement. This confirmed the hæmodynamic findings and demonstrated the improvement in architecture of the outflow tract after the repair operation.

Recurrence of Outflow Tract Obstruction. Taussig (1962) suggested that abnormal areas grew more slowly than normal so that outflow tract obstruction increased in severity with advancing age. On this basis she deferred corrective surgery until the patient had reached the age of 12 years. Increasing infundibular obstruction was also observed by Gasul, Dillon, and Vrla (1957a), Gasul *et al.* (1957b), Lynfield, Gasul, and Luan (1959), and we have observed a similar phenomenon in 10 untreated patients with Fallot's tetralogy who were studied twice by angiocardiography. The residual outflow tract obstruction in our patients probably reflected incomplete relief of obstruction at operation and not increasing obstruction, since a pressure gradient was recorded at the end of operation in the two patients with moderate residual obstruction. The long-term growth behaviour of this region can be studied only by more prolonged surveillance and reinvestigation of the patients. However, the normal pulmonary blood flow and augmented pulse pressure appears to be adequate stimulus for the growth and development of the pulmonary arteries as shown by the increase in size of the main pulmonary vessels after operation. This stimulus should, therefore, also maintain normal growth of the outflow tract.

Long-term Effects of Pulmonary Incompetence. There are few comparable studies of the long-term effects of pulmonary incompetence on cardiac function. Fish, Takaro, and Crymes (1959), Lendrum and Shaffer (1959), Smith, DuShane, and Edwards (1959), Collins, Braunwald, and Morrow (1960), Brayshaw and Perloff (1962), and Cortes and Jacoby (1962), reported individual patients with isolated pulmonary insufficiency who were symptom free, and showed that this was a benign lesion. However, heart failure does occur (Morton and Stern, 1956), and we have seen one disabled patient with post-operative pulmonary insufficiency after pulmonary valvotomy. Ellison *et al.* (1955) found that complete avulsion of the pulmonary valve in dogs was followed by no disability one year after operation. Austen *et al.* (1962) confirmed these findings. However, right ventriculotomy further compromised right ventricular function, while additional mild pulmonary stenosis reduced the severity of the incompetence. Kay and Thomas (1954), March *et al.* (1961), and Osborn *et al.* (1963) obtained similar results. There is no information about the effects of varying degrees of pulmonary insufficiency on the heart, and this was not measured directly in the present group of patients.

Although over-all cardiac function is normal and our patients are able to undertake strenuous exercise, the subtle hæmodynamic abnormalities indicate that pulmonary incompetence imposes an additional load on the right ventricle. The right ventricle handles a volume load more easily than a pressure load and many patients can tolerate an atrial septal defect with a large pulmonary blood flow for many years before heart failure develops. We feel that our patients with pulmonary insufficiency may tolerate the lesion for a long time, but may develop right heart failure in the future particularly if an inert prosthesis forms part of the wall of the ventricle. At present the outflow tract is reconstructed with great care and a transverse ventriculotomy occasionally avoids the use of the outflow patch.

Summary

Eleven patients with Fallot's tetralogy who had severe obstruction to the outflow tract of the right ventricle were studied by cardiac catheterization six months to four years after a one-stage repair operation. Angiocardiography was also performed in the five younger subjects aged 7–13 years, while measurement of the cardiac output and the response to exercise was undertaken in the six adolescents and young adults aged 15–23 years.

The long-term hæmodynamic results were good, though two patients were left with residual obstruction to the outflow tract of the right ventricle. Six others had pulmonary incompetence after extensive reconstruction of the outflow tract and main pulmonary artery.

Cine-angiocardiography demonstrated an adequate outflow tract and improvement in the size of the main pulmonary arteries.

The response of the cardiac output to exercise was normal or nearly normal. The ventilatory response to exercise was abnormal, but the reason for this was not obvious.

Although residual pulmonary incompetence produced no deleterious effect on cardiac function, the long-term results have yet to be determined. If repair is to be regarded as complete, then there should be no residual intracardiac lesion.

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